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Trends in record-breaking temperatures for the conterminous United States

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[1] In an unchanging climate, record-breaking temperatures are expected to decrease in frequency over time, as established records become increasingly more difficult to surpass. This inherent trend in the number of record-breaking events confounds the interpretation of actual trends in the presence of any underlying climate change. Here, a simple technique to remove the inherent trend is introduced so that any remaining trend can be examined separately for evidence of a climate change. As this technique does not use the standard definition of a broken record, our records* are differentiated by an asterisk. Results for the period 1961–2010 indicate that the number of record* low daily minimum temperatures has been significantly and steadily decreasing nearly everywhere across the United States while the number of record* high daily minimum temperatures has been predominantly increasing. Trends in record* low and record* high daily maximum temperatures are generally weaker and more spatially mixed in sign. These results are consistent with other studies examining changes expected in a warming climate. **Citation:** Rowe, C. M., and L. E. Derry (2012), Trends in record-breaking temperatures for the conterminous United States, *Geophys. Res. Lett.*, 39, L16703, doi:10.1029/2012GL052775.

1. Introduction

[2] It is intuitive that a warming (cooling) climate will lead to an increasing frequency of extreme high (low) temperature events and a concurrent reduction in the frequency of the opposite extreme. Because extreme events are, by definition, rare, statistical analysis of trends is difficult and has generally been limited to only moderately extreme events (*i.e.*, those in the top or bottom 10%) [*Intergovernmental Panel on Climate Change*, 2007]. For record-breaking temperatures, which represent the most extreme events, the detection of trends is further confounded by the inherent decrease, for a stationary climate, in the frequency of record-breaking events as the number of years considered increases.

[3] The probability (P_n) of breaking a record in a stationary time series of independent, identically distributed (i.d.d.) random variables is a simple, well-known function of the length of the series, with $P_n = 1/N$, where N is the number of observations comprising the series [*Glick*, 1978]. Furthermore, the expected number of records in the time series is $E(R_N) =$

$\sum_{n=1}^N \frac{1}{n}$. Thus, for a time series of 30 i.d.d. observations, 3.99 records would be expected; it would take an additional 52 observations (*i.e.*, $N = 82$) to increase the expected number of records by one. Previous studies have employed complex statistical analyses to simulate the behavior of record-breaking temperatures. *Redner and Petersen* [2006] and *Benestad* [2004] used Monte Carlo simulations on a Gaussian time series to predict the probability of breaking a record and applied these predictions to real data. *Anderson and Kostinski* [2010] examined variability of record temperatures by removing a mean trend and extracting the parameter of variance alone. *Wergen and Krug* [2010] identified a relationship between drifting mean and variance governing the expected increase in record rate. Several studies including *Anderson and Kostinski* [2010] and *Benestad* [2004] explore the technique of reversibility to evaluate record temperature trends both forward and backward in time. *Meehl et al.* [2009] identified an excess of record high temperatures compared to record low temperatures over the United States since 1950, finding an approximately 2:1 ratio of record highs to record lows, but their ratio method must aggregate data from a large number of stations to avoid division by zero if no low temperature records are broken in a given year.

[4] For a stationary climate, temperatures will be expected to exceed a set threshold at a rate that remains constant over time while the rate will change if the climate is changing. However, any trend could be the result of changes in the mean or the shape of the probability density function, or some combination. Record-breaking events occur at a rate independent of the underlying probability density function, depending – for a stationary climate – only on the number of prior years [*Coumou and Rahmstorf*, 2012]. As the length of record increases, therefore, the probability of breaking a record decreases and the expected number of daily records set in a given year approaches zero, making it difficult to detect trends in the number of records due to climate change. This is especially true for records that are expected to decrease in number, such as minimum temperatures in a warming climate. Our method combines these methods by setting a threshold value with a known – and constant – probability of exceedance. The uniqueness of our study lies in its simplicity. By comparing annual numbers of record-breaking temperatures to an established baseline, trends are revealed with little effort or mathematical manipulation. Moreover, the method can be used for individual stations as well as various geographic groupings to identify trends.

2. Methods

[5] To simplify the analysis of trends in record-breaking temperatures, we will use a modified definition of when a

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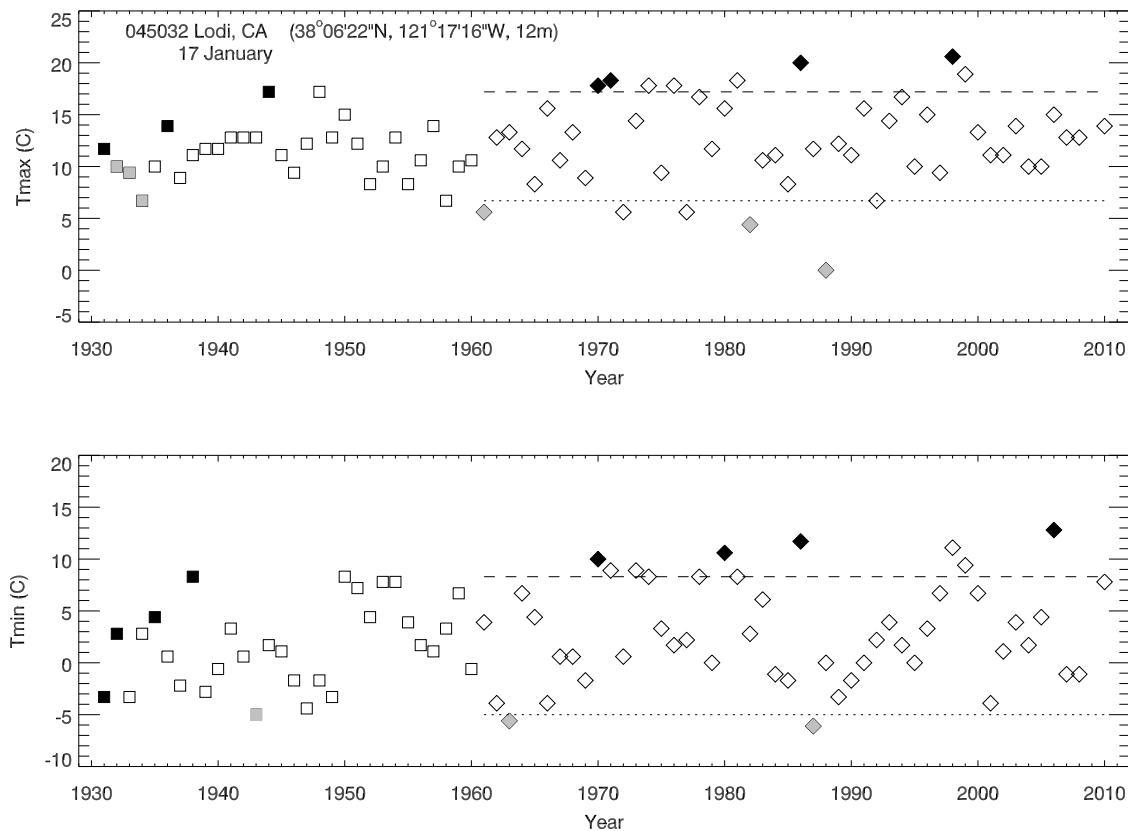


Figure 1. An example of the modified record-breaking definition used here, compared to the traditional definition, using the time series of (top) daily maximum and (bottom) daily minimum temperatures for 17 January 1931–2010 at Lodi, California. The initial 30 years (squares) are used to establish the record high (dashed line) and record low (dotted line) values for maximum or minimum daily temperature used to count records* over the remaining 50 years in the time series. Filled symbols represent the normal record-breaking events that occurred (assuming the station time series began in 1931).

record is broken. Normally, each record-breaking event establishes a new record that must be broken. In a stationary climate, records would become increasingly rare as the length of the time series increases, making it difficult to distinguish any trend due to climate change. Here we establish daily records from an initial period of 30 years and note when that temperature is exceeded, but *without* establishing a new record (Figure 1). Thus, the probability of breaking the record remains constant over the remaining portion of the time series. The remaining portion of the time series can then be analyzed for any trend without the confounding decrease inherent in normal record statistics (as these records* are not based on the standard definition of what constitutes a record-breaking event, they will be denoted with an asterisk). Moreover, as all records* are based on the same 30-year initial period, this method avoids any problems caused by time series of different length, with the inherent differences in record-setting probability, when comparing stations or grouping stations.

[6] Station time series of minimum and maximum temperatures for a specified calendar day can be considered to be comprised of independent, identically distributed random variables, as each observation is separated from the preceding and following observations in the series by a full year, making any serial correlation negligible. For any station, there are 365 separate time series of daily minimum and maximum temperatures, ignoring leap days. For each time

series, two types of records can be established – record lows and record highs – yielding four sets of daily records that can be accumulated over the course of a year: record low daily minimum (nTmin), record high daily minimum (xTmin), record low daily maximum (nTmax), and record high daily maximum (xTmax). Utilizing our modified definition, the expected number of records* of any type set in any single year at any station for a daily time series would be approximately $365/30$, or 12.2, in the absence of any climate change.

[7] The Global Historical Climate Network – Daily (GHCN-Daily) compiled by the National Climatic Data Center (NCDC) includes the 1218 stations in the conterminous United States that were selected to be included in the U.S. Historical Climate Network (USHCN) based on their long records, high quality and lack of urban bias [Durre *et al.*, 2010; Menne *et al.*, 2010]. While these stations are not free of all inhomogeneities due to, for example, changes in observation time, equipment changes and station relocations, they represent the best long-term daily climate record for the United States. From these stations, only those with no more than 10% missing data for the period 1931–2010 were selected, resulting in 748 stations. No attempt was made to replace missing data, as it is unlikely that any reasonable attempt to do so would produce a reliable record* temperature.

[8] The first 30 years (1931–1960) were used to establish a set of daily records, using the traditional definition of a record. The inclusion of the 1930s – the warmest decade on

Table 1. Distribution by Sign of Significant Linear Trends in the Number of Annual Records* by Record Type for Stations and Regions

	Trend	Significant Station (Total, If Different)				Significant Regional (Total, If Different)			
		nTmin	xTmin	nTmax	xTmax	nTmin	xTmin	nTmax	xTmax
Negative	Significant	485 (672)	36 (175)	165 (411)	37 (246)	9	0	2 (5)	0
	MST ^a (F)	−0.455 (89.65)	−0.169 (25.90)	−0.196 (42.95)	−0.173 (36.31)	−0.225 (72.85)	N/A	−0.063 (4.61)	N/A
	GST ^b (F)	−0.925 (56.31)	−0.215 (10.79)	−0.343 (35.27)	−0.600 (22.76)			−0.069 (4.26)	
	Positive	9 (62)	320 (559)	94 (323)	155 (487)	0	8 (9)	0 (4)	2 (9)
Positive	Significant	9 (62)	320 (559)	94 (323)	155 (487)	0	8 (9)	0 (4)	2 (9)
	MST ^a (F)	0.443 (14.84)	1.201 (106.44)	0.251 (23.87)	0.713 (47.22)	N/A	0.188 (43.37)	N/A	0.188 (15.85)
	GST ^b (F)	0.310 (9.20)		0.383 (7.32)	0.873 (26.29)				

^aMST: most significant trend (largest F statistic).

^bGST: greatest significant trend (largest linear trend) if different than MST.

record for much of the U.S. – represents a trade-off among several competing factors. We considered 30 years to be a minimum length for the “establishing” period and needed an even longer period over which to compute with confidence any trends in the number of records*. Moreover, we wanted to include as many stations as possible in the study and also ensure adequate spatial coverage of the entire conterminous U.S. Choosing an establishing period ending prior to and not including the 1930s (*i.e.*, beginning in 1901 or earlier) would have resulted in very poor spatial coverage, especially west of the 100th meridian, a region shown by *Meehl et al.* [2009] to have a larger excess of record high temperatures since 1950. Alternatively, starting the establishing period in 1941 would have shortened the trend analysis period by a decade. Starting in 1911 or 1921 would have lengthened the analysis period but would still have included the 1930s in the establishing period and would have resulted in poorer spatial coverage, notably in west Texas and Wyoming but also, for a 1911 starting year, Pennsylvania and Virginia. Given these considerations, the inclusion of the 1930s in the establishing period is unavoidable. However, it must be acknowledged that the large number of record high temperatures set in that decade – many of which still stand – has the potential to skew the results of any study of extreme temperatures, including the present one. Including the 1930s in the analysis period would likely result in a large number of maximum records* at both the beginning and the end of the trend analysis period (and, conversely, small numbers of minimum records*) and no clear linear trend of any kind. On the other hand, if – as we ultimately decided – the 1930s are part of the base period, they potentially set a “high bar” for establishing records* during the trend analysis period. This means that trends consistent with a warming climate will only be significant if, in fact, the warming has caused the observed temperatures to clear that high bar.

[9] Stations containing an unexpectedly high number of records* in any single year (*i.e.*, more than 90 records in any year, or ~7.5 times the expected number) were eliminated from consideration, reducing the number of stations considered to 734. Almost without doubt, setting 90 daily records* (of a single type) in one calendar year (*i.e.*, approximately 1 of every 4 days set a record*) must be the result of non-climatic factors that are undocumented in NCDC’s records. It is important to note, however, that the 14 stations that were eliminated for these large numbers of records* represented all

four record* types (8 nTmin, 5 xTmin, 2 nTmax, and 1 xTmax; 2 stations had excessive records of two types). Moreover, 8 of the stations had significant trends consistent with a warming climate, while only one had significant trends consistent with a cooling climate (and only one of the four record* types was significant at this station). Of the remaining 5 stations that were eliminated, 4 showed significant trends that were mixed (some consistent with warming, some not) and one had no significant trend for any record* type.

[10] If these large numbers of records were physically real, they most likely would occur at stations that set extremely high maximum records (or, less likely, extremely low minimum records) during the 1931–1960 period. We should therefore expect that the excessively large numbers of records* would be clustered at the beginning (cooler part) of the analysis period for nTmin and nTmax, and at the end (warmer part) of the analysis period for xTmin and xTmax. An inspection of the annual record* time series for these stations shows no consistent pattern for these stations. For the majority (9 of 14) of these stations, the excessive number of records was clearly an outlier (more than twice the next highest number of annual records* of that type) and occurred in the expected part (beginning or end) of the time series as often as either at the “wrong” end or in the middle.

[11] Linear trends in the annual number of records* of each type for each of these stations were computed over the 50-year period 1961–2010. Only trends significant at the 95% level are considered further.

3. Results

[12] Of the 734 stations studied, 494 have significant trends in the annual number of record* low daily minimum temperatures (nTmin), only 9 of which are positive (a 55:1 ratio), which is consistent with a warming climate (Table 1). The 9 significant positive trends are of smaller magnitude (Table 2) than the significant negative trends and are generally widely scattered (Figure 2a). For the most part, stations with insignificant trends are intermixed with significant trends, except in the Montana/Idaho area. Strong negative trends are found along the Great Lakes and Ohio Valley as well as the Northeastern seaboard.

[13] When the nTmin record* data are accumulated for each of the 9 NCDC standard climate regions [*Karl and*

Table 2. Distribution by Magnitude of Significant Linear Trends in the Number of Annual Records* by Record Type for Stations and Regions

Trend		Significant Station (Total, If Different)				Trend		Significant Regional (Total, If Different)			
		nTmin	xTmin	nTmax	xTmax			nTmin	xTmin	nTmax	xTmax
−1.25	−1.00	0	0	0	0	−0.25	−0.20	2	0	0	0
−1.00	−0.75	2	0	0	0	−0.20	−0.15	3	0	0	0
−0.75	−0.50	8	0	0	1	−0.15	−0.10	1	0	0	0
−0.50	−0.25	121	0	7	0	−0.10	−0.05	3	0	2	0
										(3)	
−0.25	0.00	354	36	158	36	−0.05	0.00	0	0	0	0
		(541)	(175)	(404)	(246)					(2)	
0.00	0.25	6	241	87	124	0.00	0.05	0	0	0	0
		(59)	(480)	(316)	(456)				(1)	(4)	(5)
0.25	0.50	3	67	7	22	0.05	0.10	0	3	0	1
											(3)
0.50	0.75	0	7	0	5	0.10	0.15	0	3	0	0
0.75	1.00	0	4	0	4	0.15	0.20	0	2	0	1
1.00	1.25	0	1	0	0	0.20	0.25	0	0	0	0

Koss, 1984] and normalized by the number of stations in that region, all regions have significant negative trends (Figure 3a), with the strongest trends in the Central and Northeast regions.

[14] For record* high daily minimum temperature (xTmin), 356 stations have significant trends (Table 1), with only 36 of them negative (an almost 9:1 ratio), again consistent with a warming climate. The negative trends are

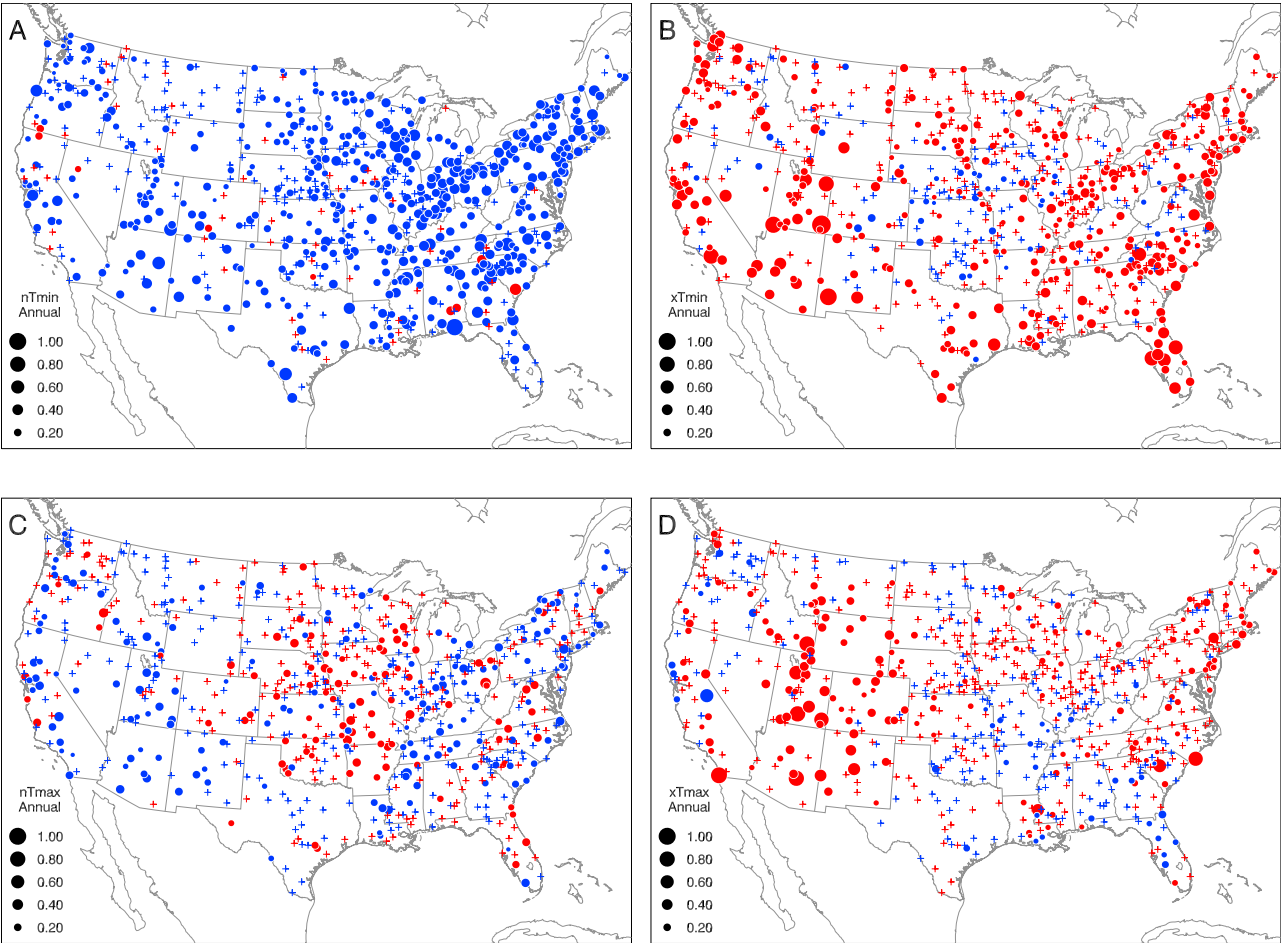


Figure 2. Trends in the number of annual record* temperatures for the conterminous United States for (a) low daily minimum temperature (nTmin), (b) high daily minimum temperature (xTmin), (c) low daily maximum temperature (nTmax), and (d) high daily maximum temperature (xTmax). Positive trends (increasing number of records*) are red and negative trends are blue. The area of the symbol is proportional to the magnitude of the trend. Stations with trends not significant at the 95% level are denoted by a plus sign (+), using the same color association.

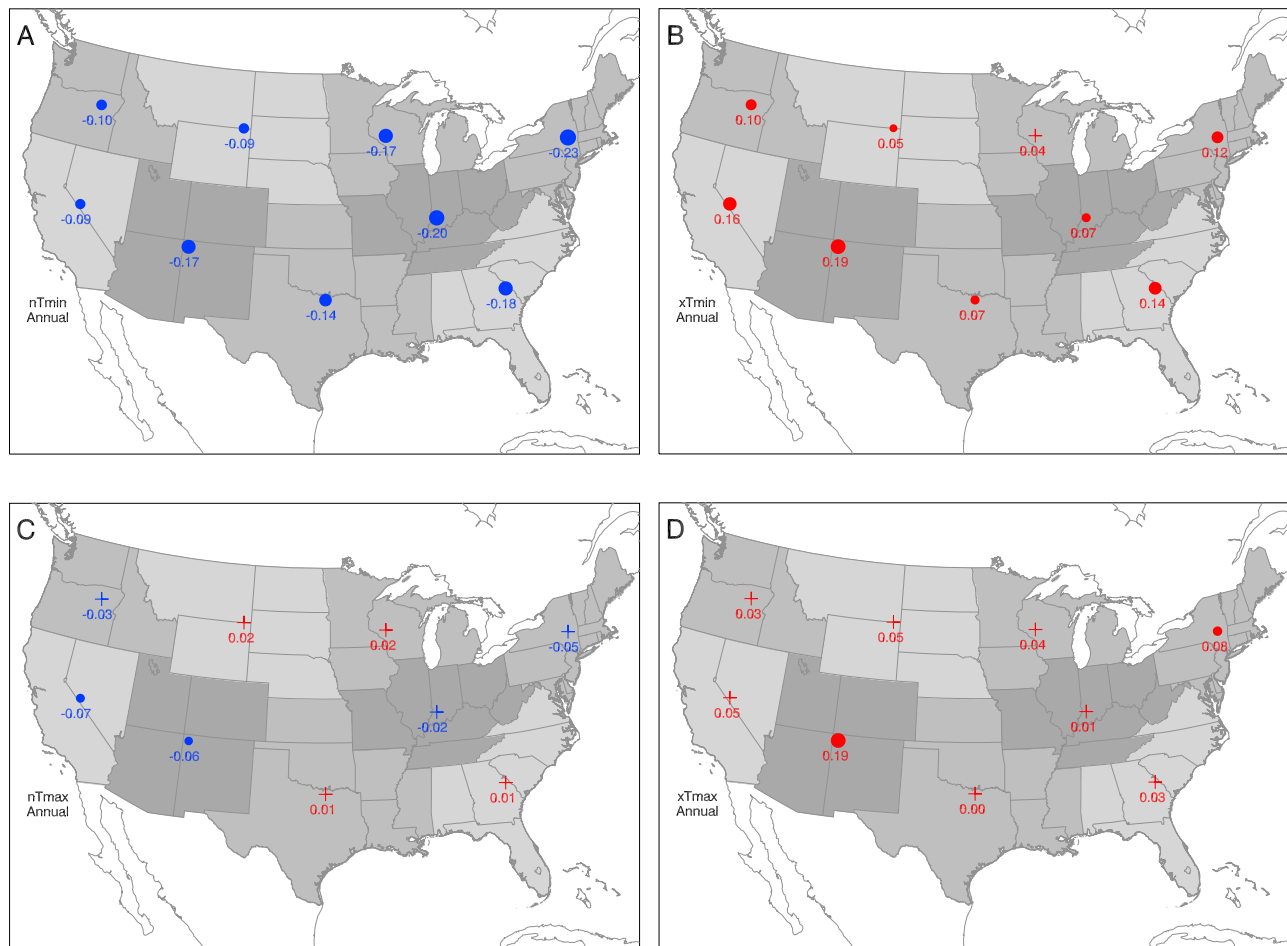


Figure 3. Trends in the normalized number of annual record* temperatures NCDC climate regions for the conterminous United States for (a) low daily minimum temperature (nTmin), (b) high daily minimum temperature (xTmin), (c) low daily maximum temperature (nTmax), and (d) high daily maximum temperature (xTmax). Positive trends (increasing number of records*) are red and negative trends are blue. The area of the symbol is proportional to the magnitude of the trend. Regions with trends not significant at the 95% level are denoted by a plus sign (+), using the same color association. The actual trend (records* per year) for each region is indicated under the symbol.

small ($<0.25/\text{year}$, Table 2) and most are located in the Prairie and Central Plains states (Figure 2b); even in this region, there is an almost equal number of significant positive trends. The strongest positive trends are found in the Southwest, with somewhat weaker positive trends along the West Coast and the Florida peninsula.

[15] All NCDC regions have positive trends (Figure 3b), with all except the East North Central significant. The strongest trends are in the Southwest, West and Northwest regions.

[16] There are fewer significant trends for record* low daily maximum temperature (nTmax) and these are more evenly distributed by sign (Table 1), with 165 negative and 94 positive (1.75:1). Moreover, the magnitude of the trends – both positive and negative – are the smallest of any of the 4 record* types (Table 2). Most of the significant positive trends are found in the Central Plains and Prairie States, extending, to a lesser degree, into the Ohio Valley, as well as the Mid-Atlantic region (Figure 2c). Significant negative trends are found in the Southwest, the West Coast and along the western flanks of the Appalachian Mountains and into the Lower Mississippi Valley. While these results are also

consistent with a warming climate, the signal is not as clear nor as strong as for daily minimum temperature records*.

[17] For the NCDC regions, there are 5 negative and 4 positive trends, with only 2 of the negative trends (Southwest and West) significant (Figure 3c).

[18] Daily maximum record* high temperature (xTmax) has the fewest (192) significant trends (Table 1), of which 155 are positive (4.2:1). Except for a single station in California (Yosemite Park HQ), the significant negative trends are rather small ($<0.25/\text{year}$, Table 2). Clusters of significant negative trends are found in the Southeast (Florida/Georgia) and central US (Arkansas/Missouri/eastern Kansas). Large ($>0.50/\text{year}$), significant positive trends are primarily located in the Southwest and Northern Rockies (where there are no significant negative trends). Generally smaller, but still significant, positive trends are found in the Carolinas, the mid-Atlantic states and New England, as well as along the West Coast (Figure 2d).

[19] All regional trends are positive (Figure 3d), but only 2 are significant (Southwest and Northeast).

[20] While our results are consistent with a warming climate, they could also be the result of shorter, decadal climate

variations due to, for example, the Pacific Decadal Oscillation (PDO) or Atlantic Multidecadal Oscillation (AMO). During the 1961–2010 analysis period, the PDO started in a predominantly negative phase through 1979, then entered a predominantly positive phase through approximately 2000, after which it has oscillated in sign. The AMO started the period positive, but decreasing, reached a low in 1975 and has been increasing since then, reaching its 1961 level in the late 1990s. These decadal scale climate variations could mimic the effects of global warming (*i.e.*, an enhanced warming signal in the record*-breaking temperature trends), but only in those regions and seasons for which the PDO (or the AMO) is positively correlated with temperature. For the PDO, this correlation has been documented only for cool-season temperatures in the Pacific Northwest [Mantua and Hare, 2002]. The correlation between PDO and temperature is negative during the cool season in the Southeast and along the Gulf Coast [Mantua and Hare, 2002]. This latter effect would be manifested by a diminished warming signal in the record*-breaking temperature trends. For the AMO, the major correlation with temperatures is a positive one over the eastern U.S. during summer with a smaller correlation of opposite sign around the Great Lakes and Northeast in spring [Sutton and Hodson, 2005, 2007]. Neither of the correlations between temperatures in the United States and the AMO is as strong as that with the PDO.

[21] The influence of these decadal scale climate variations on record* temperatures can be investigated by computing trends separately for different seasons. For example, trends for cool-season and warm-season records* should, were the PDO a major influence on these trends, exhibit significant differences between seasonal – and between seasonal and annual – trends in the Pacific Northwest and Southeast/Gulf Coast. The analysis of this expected influence completes the following discussion of trends in seasonal temperature records*.

[22] Overall, there are fewer significant trends in the number of records* of each type for all four standard seasons (DJF, MAM, JJA and SON). The dominance of decreasing trends in nTmin records* is maintained in all seasons, with the magnitude of the dominance increased, relative to the annual results, in winter and summer and decreased in the transitional seasons (Figures S1–S4 in the auxiliary material).¹ Seasonal trends in xTmin and xTmax records* largely exhibit the same spatial patterns as the annual trends for all seasons except winter, for which there are a number of additional significant decreasing trends for the Northwest and northern California and, for xTmin, extending into Montana. The magnitudes of the increasing trends in the non-winter seasons are generally larger than the annual trends, especially in summer and, to a lesser extent, autumn. For annual trends, the most spatially mixed results were for nTmax; this continues to hold for the transition months. However, increasing trends in summer are generally larger than the corresponding annual trends, especially in the central U.S. between the Mississippi River and the Rocky Mountains, while decreasing winter trends are larger than the corresponding annual trends over the rest of the country.

[23] Comparing trends in records* for the warm half-year (April–September) and cool half-year (October–March) to annual trends confirms the seasonal results just described

(Figures S5–S6). Trends in nTmin records* are consistent throughout the year while trends in xTmin and xTmax records* are largely controlled by trends in the warm part of the year. Again, seasonal control on trends in nTmax records* depend on the sign of the trend, with increasing trends in the center of the country primarily the result of the warm season and decreasing trends elsewhere the result of decreasing trends throughout the year.

[24] The Pacific Northwest and Southeast/Gulf Coast – those regions expected to be influenced by the PDO – exhibit no apparent enhancement or damping of trends during the cool season. Considering the possible influence of the AMO, record*-breaking trends during summer are somewhat enhanced for xTmin and xTmax, some spring trends consistent with warming are lessened somewhat for xTmin, and some trends in nTmax inconsistent with warming are slightly enhanced. But, in both seasons, the changes are more general across the U.S. and not limited to areas correlated to the AMO. These results support the conclusion that the trends in records* across the U.S. are the result of the general warming trend and not decadal climate variability.

4. Conclusions

[25] Recent years have seen a renewed interest in the study of record-breaking temperatures and the impact of global warming on these most extreme events. Several studies have used statistical models to simulate changes in the expected number of records as climate warms. These models range from simple linear drift of the mean [Wergen and Krug, 2010] to more elaborate Monte Carlo models with linear or nonlinear trends [Newman *et al.*, 2010; Rahmstorf and Coumou, 2011] and serial correlations [Redner and Petersen, 2006; Newman *et al.*, 2010]. Because of the inherent complexity in these latter methods, they have generally been used to investigate only a single, or a small number of, observed temperature time series. As a result, their findings are difficult to apply generally and can be contradictory, especially when only one or two observed series are investigated. For example, Redner and Petersen [2006] found no evidence of a change in the frequency of record-breaking daily temperatures in Philadelphia while Newman *et al.* [2010] concluded that the rates of record daily minimum temperatures for Mauna Loa reflect the influence of a warming trend. While these contradictory findings could be attributed to regional variations in the warming rate, Rahmstorf and Coumou [2011] determined that any increase in the numbers of records is dependent on the ratio of the warming trend to the short-term variability. For daily data, the variability is generally much larger than the warming trend and results from single time series cannot be considered conclusive. For monthly temperature time series or data averaged over a large number of stations, such as global mean temperature, variability is of the same magnitude or smaller than the trend and trends in records can be attributed to the overall warming trend [Benestad, 2004; Newman *et al.*, 2010; Rahmstorf and Coumou, 2011]. Using multiple datasets of European and American temperatures, Wergen and Krug [2010] concluded that a linear increase in mean temperature “significantly affects the rate of occurrence of new temperature records.”

[26] Meehl *et al.* [2009] employed a relatively simple, intuitive approach by taking the ratio of the annual total number of record high daily maximum temperatures to

¹Auxiliary materials are available in the HTML. doi:10.1029/2012GL052775.

record low daily minimum temperatures at nearly 2000 locations across the U.S. They found that this ratio has been increasing since 1970 and had reached a value of approximately 2 by the beginning of the 21st century. They also found that this ratio was even larger for the western U.S., where the rate of warming has been higher. Most of the increase in the ratio was attributed to a more rapid decrease in the number of record low daily temperatures compared to the expected decrease due to the lengthening time series, with the decrease in record high daily temperature at a rate closer to that expected.

[27] Our findings also are consistent with what is expected for a warming climate with increasing numbers of record* highs and fewer record* lows for both daily minimum and daily maximum temperatures over the past 50 years. Nationwide, the trends are larger and more robust for daily minimum temperature, in agreement with studies that have shown that climate change signals manifest themselves more clearly in minimum temperatures [Alexander *et al.*, 2006; Brown *et al.*, 2008; Portmann *et al.*, 2009].

[28] While aggregating stations by region can help to clarify regional patterns, the resulting trends are smaller as stations with trends of opposite sign are included. However, all significant trends at the regional level are consistent with a warming climate.

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Auxiliary Material for Paper 2012GL052775

Trends in record-breaking temperatures for the conterminous United States

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Introduction

These figures present seasonal (DJF, MAM, JJA, SON) and half-year (Oct-Mar and Apr-Sep) trends in the number of record* daily minimum and daily maximum temperatures.

2012gl052775-fs01.pdf

Figure S1. Trends in the number of winter (DJF) record* temperatures for the conterminous United States for (a) low daily minimum temperature (nTmin), (b) high daily minimum temperature (xTmin), (c) low daily maximum temperature (nTmax), and (d) high daily maximum temperature (xTmax). Positive trends (increasing number of records*) are red and negative trends are blue. The area of the symbol is proportional to the magnitude of the trend. Stations with trends not significant at the 95% level are denoted by a plus sign (+), using the same color association.

2012gl052775-fs02.pdf

Figure S2. Trends in the number of spring (MAM) record* temperatures for the conterminous United States for (a) low daily minimum temperature (nTmin), (b) high daily minimum temperature (xTmin), (c) low daily maximum temperature (nTmax), and (d) high daily maximum temperature (xTmax). Positive trends (increasing number of records*) are red and negative trends are blue. The area of the symbol is proportional to the magnitude of the trend. Stations with trends not significant at the 95% level are denoted by a plus sign (+), using the same color association.

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Figure S3. Trends in the number of summer (JJA) record* temperatures for the conterminous United States for (a) low daily minimum temperature (nTmin), (b) high daily minimum temperature (xTmin), (c) low daily maximum temperature (nTmax), and (d) high daily maximum temperature (xTmax). Positive trends (increasing number of records*) are red and negative trends are blue. The area of the symbol is proportional to the magnitude of the trend. Stations with trends not significant at the 95% level are denoted by a plus sign (+), using the same color association.

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Figure S4. Trends in the number of autumn (SON) record* temperatures for the conterminous United States for (a) low daily minimum temperature (nTmin), (b) high daily minimum temperature (xTmin), (c)

low daily maximum temperature (nTmax), and (d) high daily maximum temperature (xTmax). Positive trends (increasing number of records*) are red and negative trends are blue. The area of the symbol is proportional to the magnitude of the trend. Stations with trends not significant at the 95% level are denoted by a plus sign (+), using the same color association.

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Figure S5. Trends in the number of cool season (October-March) record* temperatures for the conterminous United States for (a) low daily minimum temperature (nTmin), (b) high daily minimum temperature (xTmin), (c) low daily maximum temperature (nTmax), and (d) high daily maximum temperature (xTmax). Positive trends (increasing number of records*) are red and negative trends are blue. The area of the symbol is proportional to the magnitude of the trend. Stations with trends not significant at the 95% level are denoted by a plus sign (+), using the same color association.

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Figure S6. Trends in the number of warm season (April-September) record* temperatures for the conterminous United States for (a) low daily minimum temperature (nTmin), (b) high daily minimum temperature (xTmin), (c) low daily maximum temperature (nTmax), and (d) high daily maximum temperature (xTmax). Positive trends (increasing number of records*) are red and negative trends are blue. The area of the symbol is proportional to the magnitude of the trend. Stations with trends not significant at the 95% level are denoted by a plus sign (+), using the same color association.

Table 1. Distribution by Sign of Significant Linear Trends in the Number of Annual Records* by Record Type for Stations and Regions

	Trend	Significant Station (Total, If Different)				Significant Regional (Total, If Different)			
		nTmin	xTmin	nTmax	xTmax	nTmin	xTmin	nTmax	xTmax
Negative	Significant	485 (672)	36 (175)	165 (411)	37 (246)	9	0	2 (5)	0
MSTa (F)	-0.455 (89.65)		-0.169 (25.90)		-0.196 (42.95)		-0.173 (36.31)		-0.225 (72.85)
(4.61)	N/A								
GSTb (F)	-0.925 (56.31)		-0.215 (10.79)		-0.343 (35.27)		-0.600 (22.76)		-0.069 (4.26)
Positive	Significant	9 (62)	320 (559)	94 (323)	155 (487)	0	8 (9)	0 (4)	2 (9)
MSTa (F)	0.443 (14.84)		1.201 (106.44)		0.251 (23.87)		0.713 (47.22)		N/A
	0.188 (15.85)								0.188 (43.37)
GSTb (F)	0.310 (9.20)			0.383 (7.32)		0.873 (26.29)			N/A

aMST: most significant trend (largest F statistic).

bGST: greatest significant trend (largest linear trend) if different than MST.

Table 2. Distribution by Magnitude of Significant Linear Trends in the Number of Annual Records* by Record Type for Stations and Regions

Trend	nTmin	Significant Station (Total, If Different)				Trend	nTmin	Significant Regional (Total, If Different)			
		xTmin	nTmax	xTmax	nTmin			xTmin	nTmax	xTmax	nTmin
-1.25	-1.00	0	0	0	0	-0.25	-0.20	2	0	0	0
-1.00	-0.75	2	0	0	0	-0.20	-0.15	3	0	0	0
-0.75	-0.50	8	0	0	1	-0.15	-0.10	1	0	0	0
-0.50	-0.25	121	0	7	0	-0.10	-0.05	3	0	2 (3)	0
-0.25	0.00	354 (541)	36 (175)	158 (404)	36 (246)	-0.05	0.00	0	0	0 (2)	0
0.00	0.25	6 (59)	241 (480)	87 (316)	124 (456)	0.00	0.05	0	0 (1)	0 (4)	0 (5)
0.25	0.50	3	67	7	22	0.05	0.10	0	3	0	1 (3)
0.50	0.75	0	7	0	5	0.10	0.15	0	3	0	0
0.75	1.00	0	4	0	4	0.15	0.20	0	2	0	1
1.00	1.25	0	1	0	0	0.20	0.25	0	0	0	0

